

The Magnetic Storm of August 22, 1916.

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§1. While the ultimate cause of magnetic storms has been a fruitful source of speculation, detailed enquiries into the phenomena presented by individual storms have been comparatively few. This distribution of effort is to be regretted, because, without accurate knowledge of the phenomena, theoretical investigations are apt to be barren of results. A difficulty in the way is the great complexity of the magnetic changes which take place, even at a single station, in the course of the ordinary magnetic storm. Some of these changes are undoubtedly more local and of less general significance than others, but the difficulty is to see anything but accident in the sequence of events.

Of late years an international scheme has existed for the selection of a limited number of magnetic storms annually, co-operating stations publishing copies of the magnetograms obtained on these particular days. A considerable number of records have accumulated, but few serious attempts have been made to utilise them. The most hopeful course is, I think, to start with the study of those magnetic disturbances of considerable amplitude which appear of the simplest kind.

The simplest type of disturbance one can imagine is that which would result from the gradual waxing and waning of an electric current in a fixed circuit. In such a case we should expect to see a gradual departure in each magnetic element from its undisturbed or normal value, the element passing through a maximum or minimum, and returning gradually to its undisturbed value. The changes in the several elements would be in phase, the maximum or minimum value occurring simultaneously in all.

The trace in a magnetogram in such a case would resemble fig. 1, the portions AB, DE of the trace corresponding to the normal value of the element, BD being greater or less according to the time taken by the magnetic change and the openness of the time scale. Instead of a single oscillation, we might have a double oscillation as in fig. 2, or a succession of

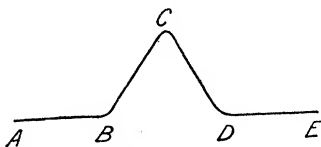


FIG. 1.

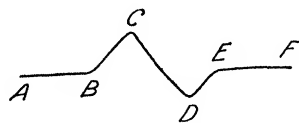


FIG. 2.

them. The movement in fig. 2 might arise from an electric current in a fixed circuit, whose direction reversed in passing through a zero value.

On the hypothesis mentioned, the departures at one and the same instant of time of any two magnetic elements from their normal values would stand to one another in a constant ratio, which obviously implies constancy of direction in the disturbance vector.

§ 2. Now, there are occasions when the magnetic curves show at least an approach to this state of matters. But supposing a source of disturbance equivalent to the fluctuations of an electric current in a fixed circuit to come into operation, one would hardly anticipate the total suspension during its action of other magnetic changes, such, for instance, as those which constitute the regular diurnal variation. Also the presence of any second source of magnetic change would interfere more or less with the regularity of shape of the magnetic curves, and it would naturally affect the different elements differently. The turning points might be accelerated in one element and retarded in another, so that the movements in the curves for different elements at a single station would no longer appear strictly in phase.

In the ordinary magnetogram, the length of trace per minute of time is only from $\frac{1}{4}$ to $\frac{1}{5}$ mm., while the dot of light producing the trace is of finite size. Thus, even under the most favourable conditions, it is difficult to fix the time of any movement to nearer than half a minute, and as the trace at a turning point has generally a finite curvature, the accuracy with which the time of reversal of a movement can be fixed is usually less than this. Thus it is usually impossible to affirm with certainty that two magnetic elements at the same station are absolutely in phase, and, conversely, the existence of a small difference of phase is apt to be rather a matter of belief than of exact demonstration.

When discussing the magnetograms obtained in 1902-4 by the National Antarctic Expedition,* along with corresponding curves from co-operating stations, I came across some cases of simultaneous, or nearly simultaneous, short movements in the traces from different stations. These movements were generally oscillatory, *i.e.*, the element tended to return towards the original undisturbed value. But the to-and-fro movements were seldom, if ever, absolutely equal, and I preferred to regard them as separate movements distinguished by the letters A and B. At a particular station the A movements had a more or less common direction, and so had the B, and the average directions for the two types were not far from being opposite to one another. In such a case, as suggested above, the departure

* 'National Antarctic Expedition, 1901-4, Magnetic Observations,' pp. 176 *et seq.*

from direct opposition in the to-and-fro movements may arise from the action of an independent source of disturbance. If so, our best course would probably be to treat the two movements as the two halves of an oscillation due to a simple source, as we might reasonably hope in this way to eliminate in considerable measure the effects of the second source of disturbance. But, on the other hand, the departure from exact opposition between the two movements may be an essential, not an accidental, feature, and if so, the conception of a to-and-fro oscillation in a given azimuth may be the reverse of helpful.

In dealing with the Eskdalemuir curves for 1913 and 1914, Mr. L. F. Richardson* came across a number of cases which he believed to represent oscillation in a fixed azimuth. These he called disturbances of class K. In other disturbances, which he called class L, he found the movements in the different elements to differ in phase.

Personally, I am inclined to think that it is at least highly exceptional for the movements in the different elements to remain absolutely in phase for any appreciable length of time. However this may be, there can be no doubt that differences in phase between the different elements are much more in evidence in some cases than others. When there is a difference of phase between the two components in, say, the horizontal plane, the azimuth of the disturbance vector in that plane continually alters. The fact that the vector diagram often represents a rotation which proceeds in one direction for a considerable time, it may be hours, the rotation being either clockwise or counter-clockwise, was first pointed out by Mr. R. B. Sangster.† Dealing with the copies of disturbed curves, published annually at Greenwich, he found no less than 70 examples of the phenomenon. Analysing them, he found the direction of rotation to be largely dependent on the hour of the day. He observed no single instance of what he called a "positive" (or clockwise) rotation between 4 P.M. and 9 P.M., while in the early morning this direction was the more common one.

§ 3. The disturbance I am now about to describe is one in which the rotation in the disturbance vector diagram is so remarkably pronounced and regular as to invite special study. It began with a "sudden commencement," especially prominent as usual in the horizontal force, at about 6 h. 30 m. P.M. on August 22, 1916, and continued until the morning of the

* Meteorological Office, 'British Meteorological and Magnetic Year Book,' Part IV, Section 2, p. 78, 1913.

† 'Roy. Soc. Proc.,' A, vol. 84, p. 85. NOTE.—Mr. Sangster really considered the vector diagram in the plane normal to the dipping needle. But the directions of rotation seen in it and in the horizontal plane are usually the same. The latter depend only on variations of the horizontal components, which are usually the most reliable.

23rd. As usual, the curves did not become really quiet for a considerable time, but no large movements took place after 5 A.M. on the 23rd, and at Kew Observatory the specially conspicuous movements took place between 7 P.M. and 11 P.M. on the 22nd. Attention is restricted here to these hours, and more especially to the interval 7.48 P.M. to 9.24 P.M. A display of aurora on the evening of the 22nd was reported from one Scottish meteorological station—Stornoway—but it does not seem to have been in any way outstanding. The duration of twilight, however, at that season would naturally interfere with the visibility of aurora in Scotland during the earlier part of the magnetic storm.

The artificial disturbances from which the Kew magnetic curves now suffer render them unsuitable for the study of minor details of most natural disturbances, but, on August 22, 1916, the natural disturbance was so large that the uncertainties connected with the measurement of the H and D (horizontal force and declination) traces were not serious. Vertical force (V) measurements at Kew are exposed to much more uncertainty. Photographic copies of the Eskdalemuir curves were kindly supplied by Dr. Crichton Mitchell, Superintendent of the Observatory. The horizontal components recorded at Eskdalemuir are not, as usual, H and D, but N and W, the north and west components. This stands somewhat in the way of optical intercomparison of the curves at the two observatories.

In fig. 3 H and D are copies, reduced to half, of the Kew horizontal force and declination traces from 7.30 P.M. to 9.30 P.M. on August 22, set to a common time scale, so that points on the same ordinate refer to the same

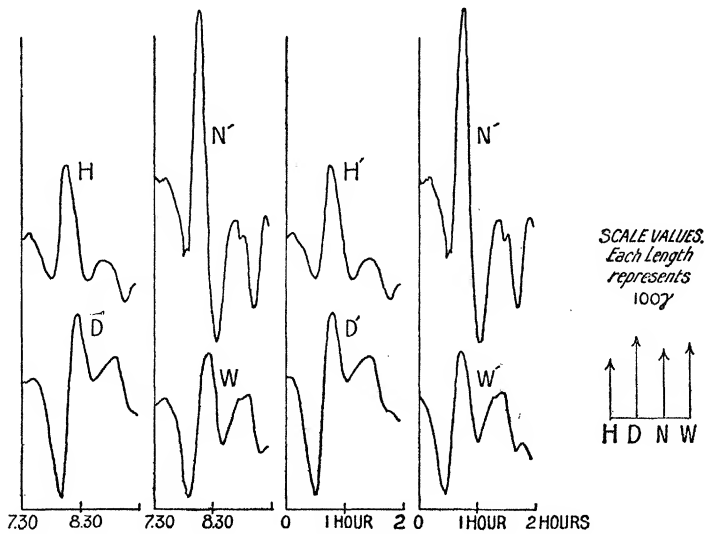


FIG. 3.

instant of time. N and W are the Eskdalemuir north and west component traces, similarly set and reduced, for the same interval. The time scales at the two observatories are closely alike, one hour being represented by about 15.3 mm. The ordinates' scale values were as follows: 1 mm. equals 6.1γ in H, 4.6γ (or $0.87'$) in D, 5.0γ in N, and 5.3γ in W. H' and D' are identical with H and D, only D' has been moved to the left relatively to H' by the equivalent of 10 minutes of time. In other words, if t be the time in minutes to which a point on a given ordinate in the D' curve answers, the point on the same ordinate in the H' curve answers to the time $t-10$. Similarly, N' and W' are the same as N and W, but for a relative displacement corresponding to about 10 minutes of time.

Declination at Kew Observatory is about 15.1° W. We may thus regard the H and D curves as showing the changes of force in two rectangular directions, the first inclined 15.1° west of north, the other 15.1° south of west. Again, while the H and D curves in fig. 3 are not in phase, the difference in phase is not large, and there is a considerable resemblance between the curves. Hence, if N and W component magnetographs had been in operation at Kew, the resemblance between the N curve and the H curve and between the W curve and the D curve would have been pretty close. It follows that the variation in the N component at Eskdalemuir was very much larger than the corresponding variation at Kew. As Eskdalemuir is not very far from the English border, the difference between the North of Scotland and the South of England may well have been twice as great as between Eskdalemuir and Kew. To arrive at an adequate conception of the variations of magnetic force during a disturbance of this type, even in such a limited area as the British Isles, obviously requires the co-operation of at least four or five well distributed stations.

It is obvious at a glance that D is not in phase with H, nor W with N. It is equally clear that, if no time difference had existed between D' and H', and between W' and N', we should have regarded either pair of curves as showing a close approach to identity of phase throughout the greater part of two hours. At the same time, the ratio of the amplitudes of the successive oscillations is not the same for the two elements, so that, even if the records had been simultaneous, the azimuth of the disturbance vector would have undergone change.

§ 4. To study details, the curves were measured at 4-minute (or very nearly 1 mm.) intervals, and, to facilitate comparison, the changes in H and D at Kew were converted into changes in N and W. The values of the elements immediately before the sudden commencement at 6.30 P.M. were accepted as normal, and it is the differences from these normal values, ΔN ,

Table I.—Departures from the "Normal" Values.

Hour, P.M., G.M.T.	Kew.			Eskdalemuir.			Hour, P.M., G.M.T.	Kew.			Eskdalemuir.		
	$\Delta N.$	$\Delta W.$	$\psi.$	$\Delta N.$	$\Delta W.$	$\psi.$		$\Delta N.$	$\Delta W.$	$\psi.$	$\Delta N.$	$\Delta W.$	$\psi.$
h. m.	γ	γ	$^{\circ}$	h. m.	γ	γ	$^{\circ}$	γ	γ	$^{\circ}$	γ	γ	$^{\circ}$
7 0	+43	+3		9 0	+14	+2		-44	-14	+73	-48	+1	-123
7 4	+45	+1		9 4	-18	+5		-44	-18	+66	-43	+6	-125
8	+39	-7		8	-27	+3		-54	-27	+64	-85	+5	-136
12	+33	-10		12	+42	-3		-51	-41	+51	-129	-32	-144
16	+30	-13		16	+39	-5		-43	-59	+32	-112	-77	-106
20	+30	-18		20	+25	-14		-44	-57	+26	-52	-80	-41
24	+29	-16		24	+31	-11		-34	-39	+22	-21	-67	-84
28	+29	-16		28	+31	-14			-37		-32	-66	-80
32	+33	-15		32	+23	-9			-37		-45	-74	-75
36	+32	-13		36	+27	-6			-35		-47	-89	-69
40	+21	-12		40	+30	-5			-23		-41	-91	-67
44	+11	-13		44	+22	-8			-27		-37	-97	-71
48	0	-20	-7	48	+12	-13	+27		-28		-41	-95	-72
52	-15	-32	0	52	-8	-29	+18		-35		-59	-42	-81
56	-17	-51	+15	56	-35	-43	+10		-47		-80	-77	-77
8 0	-5	-94	+10	10 0	-72	-93	+6		-55		-85	-73	-73
4	+28	-154	+5	4	+97	-134	+5		-57		-87	-80	-68
8	+86	-141	+6	8	+247	-128	-7		-54		-92	-72	-68
12	+130	-95	-8	12	+254	-93	-8		-52		-97	-74	-68
14	+148	-46	-9	14	+251	-43	-1		-45		-102	-61	-67
16	+134	+20	-10	16	+20	-16	+5		-43		-103	-60	-69
20	+95	+56	-3	20	+137	+37	+29		-46		-105	-58	-75
24	+81	+72	+9	24	+12	+65	+57		-47		-112	-64	-77
28	+21	+55	+20	28	-92	+63	+47		-59		-82	-74	-82
32	-49	+17	+37	32	-152	+32	+40		-61		-42	-69	-80
36	-38	+44	+40	36	-187	-32	+33		-51		-30	-56	-85
40	-29	-16	+47	40	-137	-61	+39		-38		-37	-36	-95
44	-17	-27	+48	44	-82	-42	+52		-30		-58	-35	-97
48	-11	-41	+57	48	-21	-32	+66		-30		-67	-36	-92
52	-13	-46	+70	52	-46	-12	+77		-29		-60	-36	-85
56	-13	-4	+73	56	-30	-3	+75		-32		-57	-37	-80

derivable from the ranges* of the elements, as shown in the Table, viz., at Kew $\Delta N = 211 \gamma$, $\Delta W = 226 \gamma$, $\Delta V = 80 \gamma$, and at Eskdalemuir $\Delta N = 441 \gamma$, $\Delta W = 199 \gamma$, $\Delta V = 179 \gamma$.

The range in W is slightly larger at Kew, but the Kew ranges in N and V are barely half those at Eskdalemuir. Ranges as large as 600γ in magnetic storms have been recorded, though very rarely, at Kew, but a range of 441γ in the course of 22 minutes, as presented by the N trace at Eskdalemuir, would be very notable, if not absolutely unprecedented, in any element at Kew.

The extreme steepness of the curves, especially the Eskdalemuir N curve, rendered the measurements more difficult, and the results less certain than usual, because a very small error in the time, or a very small tilt in the measuring scale, would have unusually large effects.

Exception may be taken to the normal values accepted. This is generally a difficulty. Perhaps the most approved plan is to accept as the normal value at any hour the arithmetic mean of the values at that hour on all the quieter days of the month or a selection of them. The object is to eliminate the regular diurnal variation, the contribution from which varies from hour to hour. This method is, however, not so satisfactory as it was once supposed to be, because we now know that the amplitude and character of the regular diurnal variation are considerably affected by the presence of disturbance. Also the strict application of this method to a case where measurements are taken at intervals not of one hour but of four minutes would entail so much labour as to be justifiable only if one felt assured of its marked superiority. In favour of the course adopted, it may be urged that the Kew curves at least were practically quiet up to the time of the "sudden commencement," and that the ordinary diurnal variation during the evening hours covered by the Table is so small compared with the changes which actually occurred that it is practically immaterial how we treat it.

§ 5. The results in the horizontal plane between 7.48 P.M. and 9.24 P.M. are shown as vector diagrams in fig. 4. To prevent confusion the intervals 7.48 P.M. to 8.48 P.M. and 8.44 P.M. to 9.24 P.M. are illustrated by separate diagrams, with distinct origins and axes of co-ordinates. The overlap of four minutes is intended to assist the eye in passing from consideration of the one interval to the other. The full line curves with observational points indicated by crosses refer to Kew, the dotted curves with observational points indicated by circles refer to Eskdalemuir. Unity in the forces marked on the co-ordinate axes represents 1γ . The times to which the observational points

* The ranges as shown on the Kew curves are $\Delta H = 225 \gamma$, $\Delta D = 42'$.

refer are shown, and alongside from 7.48 P.M. to 8.48 P.M. are the corresponding values of the inclination ψ .

A thing to be noticed is that the length and direction of the vector drawn from the origin to any observational point are dependent on the values accepted as normals for N and W, and so are to some extent arbitrary. If, however, we treat the normals as constants, a change in the values accepted has no influence on the shape of the curve obtained by connecting up the observational points, or on the direction in which it is described by a point travelling continuously along it. A change in the normal values accepted is really equivalent to a transfer of the origin of co-ordinates from one point to another. If, for instance, we had taken normal values for N larger by 60 γ , and for W larger by 40 γ , we should have had an origin nearly central for both the diagrams relating to the interval 7.48 P.M. to 8.48 P.M.

The diagrams are obviously described counter-clockwise throughout, and so in the direction which Mr. Sangster found to be characteristic of the evening hours at Greenwich. The outstanding feature is the regularity of outline in the diagrams for the interval 7.48 P.M. to 8.48 P.M.

If corresponding points are joined in the Eskdalemuir and Kew diagrams, it will be found that in most cases the connecting line is oriented roughly N.N.W. (or S.S.E.). Departures from this direction are seldom marked, unless the two corresponding points lie close together, when a small error in the time or in the curve measurement for either station would exert an unusually large influence on the azimuth. This suggests that the disturbance field at Eskdalemuir might be obtained by superposing on the disturbance field at Kew a field the vector in which shows but small departures from a fixed direction, this direction being roughly that of the line connecting the two stations.

§ 6. The magnetic changes constituting the regular diurnal inequality are almost certainly due in the main to electrical currents in the upper atmosphere. These changes show a clear dependence on local time, and so are presumably ultimately due to the sun. The solar influence may be purely electrical, *e.g.*, a flight of electrons, or largely thermal. If it is thermal, the difference between the diurnal variations on quiet and disturbed days, and between the diurnal variations in years of many and of few sunspots, seems to prove that the strength of the currents is not determined solely by the intensity of the thermal action, but partly by other causes. The most natural hypothesis is that these other causes reduce the electrical resistance of the upper atmosphere and so increase the magnitude of the currents to which the diurnal variation is due. The facts that the character of the diurnal inequality shows a marked dependence on the latitude, and that the phase is determined by local time,

suggest that electrical currents are present throughout the whole of the upper atmosphere, and that the phenomena are chiefly dependent on the current existing within a moderate distance of the zenith of the place.

The influence of local time is also recognisable in the case of magnetic disturbance. For instance, the main features of the phenomena presented by the vertical force at Kew during a magnetic storm can generally be foretold by reference to the hour of the day. But large magnetic disturbance in Britain is usually accompanied by aurora, as was the case on August 22, and aurora, at least in England, is usually comparatively low down towards the northern horizon. Of course, the electrical discharges causing aurora may not be confined to the regions of the sky where aurora is visible. Below a certain intensity they may be invisible and, if so, the disturbance at a station in low or mean latitudes may be mainly due to invisible currents near the zenith, and only in a minor degree to currents existing where aurora is seen.

The fact that the disturbance of August 22 was much larger at Eskdalemuir than at Kew might mean that the disturbance at both places was mainly due to electrical currents restricted to a limited area, considerably nearer to Eskdalemuir than to Kew, or it might mean that electrical currents present in all latitudes were much stronger in the latitude of Eskdalemuir than in that of Kew.

Aurora is much more in evidence in Scotland, especially the North of Scotland, than in the South of England; thus, if the disturbing currents are limited to the regions of the atmosphere where aurora is visible, they would in the ordinary course be some 300 miles nearer to Eskdalemuir than to Kew. The magnetic force due to a very long straight current varies inversely as the distance from the current, while the strength of the field due to a closed electrical circuit at a distance large compared with the largest diameter of the circuit varies as the inverse cube of the distance. Thus, if the disturbance of August 22 were due to currents restricted to a definite limited portion of the atmosphere we must suppose that portion of atmosphere to have been a few hundred miles north of Eskdalemuir. It is, however, difficult to imagine how electrical currents situated a few hundred miles north of Eskdalemuir could produce the changes of field exhibited in fig. 4. A change in the sign of *W* would naturally arise if the nearer portions of current were oriented east-west, and the centre of the current area moved across the meridian of the station, and would thus naturally present itself nearly at the same time at Eskdalemuir and Kew, as was indeed the case. But we should expect the range of *W* to be greater at the nearer station, while the reverse occurred. If a current of given sign continued to flow in a straight horizontal circuit, a change would naturally

occur in the sign of ΔV when the circuit crossed the zenith of the place. But such transit would not change the direction of the horizontal component of force. It will be seen, on consulting Table I, that ΔV , while generally negative, was distinctly positive for a short time, a little after 8 P.M. at both stations. The change from $-$ to $+$ in ΔV occurred nearly, if not quite, simultaneously with a corresponding change of sign in ΔN , though ΔV reverted to the minus sign some minutes before ΔN did. A change of sign from minus to plus also took place in ΔW , but decidedly later than in the other elements. These changes of sign seem difficult to account for on the hypothesis of mere change of position in the circuit of a definite electrical current. They suggest changes in the direction of the current as well.

If the disturbance were due to electrons from the sun, these, according to Profs. Birkeland and Störmer, should describe spirals round the lines of force of the earth's magnetic field, and so should be approximately equivalent to a current following the lines of force, but not extending below the upper regions of the atmosphere. Störmer's observations and estimates—made, however, in years of sunspot minimum, when the electrons may be easier stopped—put the lower limit of aurora as usually a little less than 100 kilom. One would expect the horizontal component of force due to such a discharge to have an east-west rather than north-south azimuth, while the vertical component would naturally be small except near the margin of the area which had the discharge overhead.

In view of the many possibilities, speculations based on the phenomena seen at two stations only are unlikely to hit the mark. In cases such as the present, a third station in the North of Scotland, preferably in the Orkneys or Shetlands, would undoubtedly be more helpful than any station in central or southern Europe. It is hoped that the present paper, besides encouraging investigations at other observatories into this particular storm, may secure increased attention to the interesting phenomenon discovered by Mr. Sangster. A study of the diurnal variation in the direction of rotation of the disturbance vector in different parts of the world should lead to results of interest.